

# Pseudomorphic Bipolar Quantum Resonant-Tunneling Transistor

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**Abstract**—A bipolar tunneling transistor has been fabricated in which ohmic contact is made to the strained  $p^+$  InGaAs quantum well of a double-barrier resonant-tunneling structure. The heterojunction transistor consists of an n-GaAs emitter and collector, undoped AlAs tunnel barriers, and a pseudomorphic  $p^+$  InGaAs quantum-well base. By making ohmic contact to the p-type quantum well, the hole density in the quantum-well base is used to modulate the base potential relative to the emitter and collector terminals. With control of the quantum-well potential, the tunneling current can be modulated by application of a base-to-emitter potential. This paper details the physical and electrical characteristics of the device. It is found that the base-emitter voltages required to bias the transistor into resonance are well predicted by a self-consistent calculation of the electrostatic potential.

## I. INTRODUCTION

THERE are physical limits to the minimum size at which conventional transistors can operate [1], [2]. If still smaller and faster electron devices are to be found, then new transistor approaches are needed that are not subject to the same physical size restrictions. Recently the Bipolar Quantum Resonant-Tunneling Transistor (BiQuaRTT) has been reported [3], [4]. In this three-terminal resonant-tunneling device, tunneling transport is controlled by varying the potential of the p-type quantum well in a resonant-tunneling double-barrier (RTD) structure. The BiQuaRTT does not circumvent the scaling limitations of conventional transistor technology, but it is a precursor to other controlled-tunneling devices that could function in a smaller physical space. In this paper, we report the transport properties of an AlAs/InGaAs/AlAs pseudomorphic BiQuaRTT grown on GaAs.

Capasso *et al.* [5]–[7] have conceived of and demonstrated a resonant-tunneling bipolar transistor (RTBT) that has an undoped RTD embedded in the base of an otherwise conventional heterojunction bipolar transistor. In the RTBT the neutral p-type base layer supplies free holes to

the undoped quantum well forming a two-dimensional (2-D) hole gas; thus, the Fermi level in the RTD and the neutral p-base are aligned. The tunneling current through the device is controlled by application of base current steps, but is also affected by changing the voltage between collector and emitter since independent control of the resonant-tunneling condition is not provided.

In the BiQuaRTT, the p-doping is confined to the quantum well; 2-D holes therein are used to control the potential between the base and the emitter. In this way the electrostatic potential between the quantum well and the emitter electron reservoir is used to set the tunneling condition through the first tunnel barrier. This is a fundamental difference between the BiQuaRTT and RTBT concept. In the BiQuaRTT, the resonance condition is controlled by  $V_{be}$  independently of the collector-to-emitter voltage  $V_{ce}$ . The large 2-D holes gas density serves to screen the electric field from the quantum well and thereby decreases the modulation of the quantum-well eigenstates by the collector-base field (Stark effect). In the BiQuaRTT, negative differential resistance (NDR) is not desired in the common-emitter transistor characteristics while in the RTBT the NDR is introduced by design. The double-barrier structure in the BiQuaRTT is utilized to produce a negative transconductance in the common-emitter transistor characteristics without negative output conductance. In fact, the collector conductance is relatively small, providing dc isolation between the base and collector, which NDR devices conspicuously lack. This is preferred for most compressed-function logic circuit applications.

Another RTBT device variation has been to place the resonant-tunneling double barrier in the emitter of a bipolar transistor. Both one [8], [9] and two [10]–[12] double-barrier structures have been integrated into the device. In this configuration, the transistor characteristics are essentially described by the combination of an RTD connected in series with the emitter of a bipolar transistor.

## II. MATERIAL AND DEVICE STRUCTURE

The epitaxial material was grown by molecular-beam epitaxy in a Riber MBE-2300 system. The layer design, shown in Fig. 1, utilizes three different bandgaps across the structure: the widest bandgap layer is used for the tunnel barriers while the higher bandgap of the emitter and

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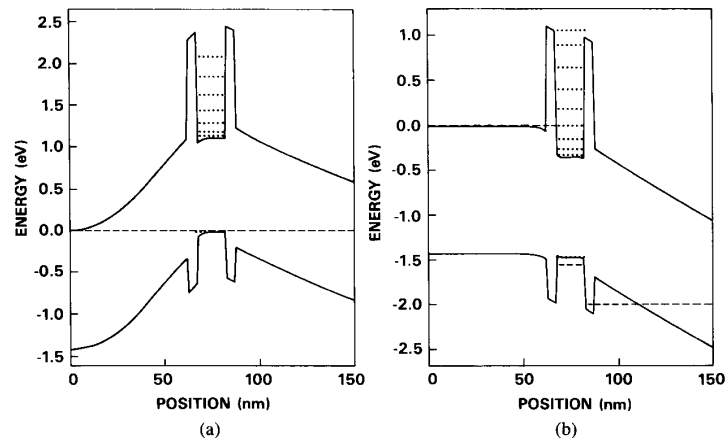
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300nm	n <sup>+</sup> GaAs	$2 \times 10^{18} \text{ cm}^{-3}$
200	n-GaAs	$5 \times 10^{17}$
25	GaAs	UNDOPED
5	AlAs	UNDOPED
5	InGaAs(x=0.23)	UNDOPED
5	p <sup>+</sup> InGaAs(x=0.23)	$1 \times 10^{19}$
5	InGaAs(x=0.23)	UNDOPED
5	AlAs	UNDOPED
25	GaAs	UNDOPED
500	n-GaAs	$2 \times 10^{16}$
500	n <sup>+</sup> GaAs	$2 \times 10^{18}$

n<sup>+</sup> GaAs SUBSTRATE

Fig. 1. Pseudomorphic BiQuaRTT material structure.

Fig. 2. Pseudomorphic BiQuaRTT energy band profile derived from a self-consistent simulation. The structure is shown in (a) equilibrium and (b) under bias to bring the emitter electron energy into resonance with the fourth allowed quantum well base state,  $V_{be} = 1.5 \text{ V}$ ,  $V_{ce} = 2.5 \text{ V}$ , 300 K. The dashed lines designate the Fermi level position; the dotted lines designate the electron and hole states in the quantum well.

collector layer relative to the quantum well base serves to confine the holes in the base at the high base-emitter voltages necessary to bring the device into resonance. Moderate emitter doping provides a relatively narrow emitter electron energy distribution and a low valley current through the tunneling structure. A lightly doped collector layer is used to obtain a low base-collector conductance.

Starting from the substrate, the structure consists of a 500-nm n<sup>+</sup> GaAs buffer layer below a 500-nm n-GaAs collector. The RTD base is symmetric about a 5-nm InGaAs Be-doped layer in the center of the quantum well. InGaAs spacer layers of 5 nm on either side of the 5-nm Be-doped layer bring the quantum well width to 15 nm. This  $\text{In}_{0.23}\text{Ga}_{0.77}\text{As}$  layer at a total thickness of 15 nm is less than the critical layer thickness for dislocation formation [13] and was chosen this large to ease the doping and contacting requirements. AlAs tunnel barriers of 5-nm thickness and 25-nm undoped GaAs spacer layers bound the quantum well on either side. The thick undoped layers are used in order to provide a neutral base with free holes. (Thinner AlAs tunnel barriers should improve the resonant tunneling characteristics of the device.) A 20-nm

GaAs emitter region, doped to  $5 \times 10^{17} \text{ cm}^{-3}$ , is utilized on top of the quantum-well base, followed by a 300-nm n<sup>+</sup> contact layer.

Room-temperature energy band diagrams for the device are shown in Fig. 2: (a) in equilibrium and (b) under bias into resonance with  $V_{be} = 1.55 \text{ V}$  and  $V_{ce} = 2.0 \text{ V}$ . The n-type GaAs emitter is at left, with the p-type InGaAs quantum well base in the center, and the n-GaAs collector at the right.  $\Gamma$ -point AlAs tunnel barriers are assumed. The dashed lines indicate the Fermi level position, while the dotted lines indicate the eigenstates for electrons or holes within the well. These profiles are obtained from a self-consistent (zero current) solution of Poisson's equation for the electrostatic potential. The free-electron densities in the emitter and collector are calculated from the Fermi distribution for semiclassical electrons. The allowed carrier energies in the base are obtained from a solution of Schrodinger's equation. The hole density in the base is determined by integrating the product of the quantum-well-base 2-D density of states and the Fermi distribution in the base over energy.

From the energy band profiles it can be seen that the

quantum-well contact can be used to reduce the potential energy of the quantum-well electron states to the point where they are equal with the electron energies in the emitter. At this value of  $V_{be}$ , resonant tunneling across the base can occur. Further increase in  $V_{be}$  lowers the resonant energy below the emitter electron energies, and the tunneling current is suppressed. Thus with increasing  $V_{be}$ , a decreased collector current is expected and therefore a negative transconductance [3].

A non-self-aligned process utilizing conventional photolithography and lift-off metallizations is used to form the transistor. Contact to the quantum well is achieved by implantation of Be. The triple Be implant of  $1 \times 10^{15} \text{ cm}^{-2}$  at energies of 30, 80, and 160 keV is sufficient to convert the  $2 \times 10^{18} \text{ cm}^{-3}$  n-type surface layer conductivity to p-type. The implantation is activated by rapid thermal annealing (RTA) at  $750^\circ\text{C}$  for 10 s. The implanted base region is isolated from the emitter by wet chemical etching to prevent the turn-on of the lateral base-emitter p-n junction.

### III. CHARACTERIZATION

Anomalous redistribution of Be in MBE-grown GaAs has been previously reported [14], [15]. In the BiQuaRTT, diffusion of Be beyond the quantum well must be suppressed to ensure independent control of the quantum-well potential. Secondary ion mass spectroscopy (SIMS) was used to profile the physical concentration of Be and Al in the BiQuaRTT material structure. The intensity of the Al and Be signals as measured by SIMS is shown in Fig. 3 and plotted as a function of sputtering time into the structure. The Be signal appears within the two Al peaks indicating that the Be has not diffused beyond the AlAs tunnel barriers. Further SIMS measurements reveal that the Be remains confined to the quantum well after RTA and that the implantation of Be extends to the quantum well.

Hall-effect measurements were made on a bridge test structure formed on a companion BiQuaRTT wafer with a 25-nm quantum-well base to verify the existence of free holes in the quantum-well base. An eight-contact bridge specimen was formed by mesa etching through the  $n^+$  top layer and the quantum-well base. As with the transistor fabrication, ohmic contact to the quantum well was provided by implantation and RTA. Hall-effect measurements (4 K) revealed a positive Hall voltage, indicating p-type material and thus giving independent confirmation of free holes in the base. A mobility of  $780 \text{ cm}^2/\text{Vs}$  and a hole density of  $4 \times 10^{18} \text{ cm}^{-3}$  were inferred with simple geometry and single-carrier assumptions.

### IV. TRANSPORT CHARACTERISTICS

Common-emitter transistor characteristics for the pseudomorphic BiQuaRTT of (Fig. 1) are shown in Fig. 4. The device shows a gain of approximately 13 at room temperature with a maximum current density of  $2.1 \times 10^5 \text{ A/cm}^2$ . When the device cools to 77 K, the current density and gain are maintained although at higher base volt-

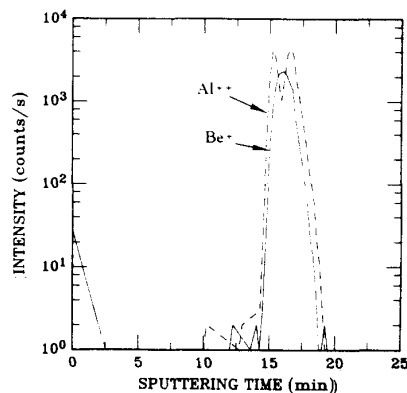


Fig. 3. SIMS profile of the pseudomorphic BiQuaRTT showing concentration profiles of singly ionized Be and doubly ionized Al.

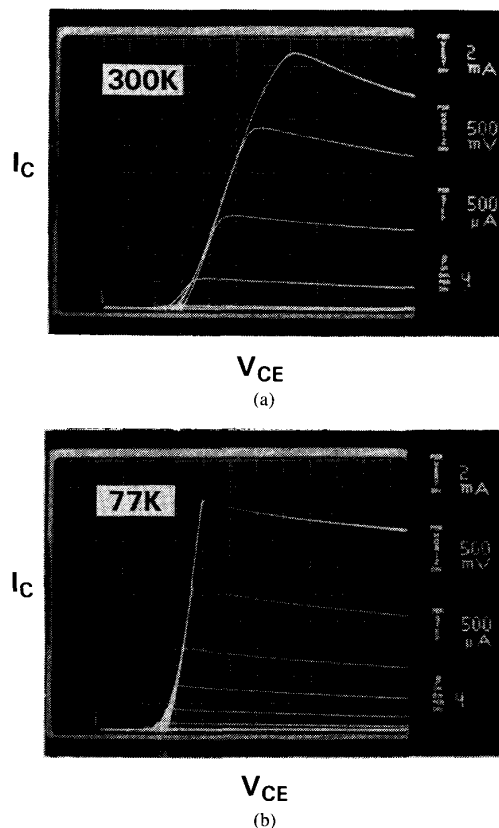


Fig. 4. Pseudomorphic BiQuaRTT common-emitter transistor characteristics at (a) room temperature and (b) 77 K. Emitter area is  $9 \mu\text{m}^2$ ; base-to-emitter contact spacing is  $7 \mu\text{m}$ .

ages. At 77 K, the emitter resistance is decreased (mobility enhancement) and the transition to the saturation regions is more abrupt. At larger collector currents, a negative output conductance region is apparent. As will become apparent, the negative conductance is not due to the RTD structure, since it occurs at larger base-emitter voltages than are required for resonant tunneling. (Our examination of this negative conductance indicates that it arises from interband scattering in the GaAs or AlAs con-

duction band.) A large collector-emitter offset voltage is also apparent in Fig. 4 and occurs because of the large series base resistance of the non-self-aligned process. For low collector-emitter voltage ( $V_{ce} \sim < 1.5$  V) and for the base currents shown (Fig. 4), the base-collector junction turns on before the base-emitter junction giving rise to a negative collector current not visible in this quadrant of the current-voltage characteristics.

Under base voltage bias, negative transconductance is not observed; however, this can be understood in terms of the material structure. Referring back to the energy band diagram of Fig. 2(b), the first resonance can be predicted to occur through the  $n = 4$  quantum well state at  $V_{be} = 1.55$  V. Additional resonances can be anticipated at 1.73 and 2.13 V through the  $n = 5$  and  $n = 6$  eigenstates and beyond. The device was therefore operated with base voltage steps about this bias point. The resonances are most readily distinguished by measuring the collector current as  $V_{be}$  is monotonically increased with constant  $V_{ce} = 2.5$  V; see Fig. 5. With increasing  $V_{be}$ , the potential energy of the allowed states in the quantum well is lowered with respect to the electrons in the emitter. In the measurement at room temperature (dashed line), no evidence of tunneling current modulation is observed. However, with the device cooled to 77 K, clear inflections in the collector current are observed. By taking the derivative of the collector current with respect to the base-emitter voltage (right-hand axis of Fig. 5), we determine the measured base-emitter voltages at resonance to be approximately 1.6, 1.9, and 2.4 V. This is in remarkable agreement with the resonances expected from the electrostatic profile, 1.55, 1.73, and 2.13 V. Series resistance pushes the measured inflections out to higher base-emitter voltages, which is consistent with these measurements. The fact that negative transconductance is not observed implies that inelastic transport processes in this device are comparable to the resonant-tunneling current. This is due to the low resonant-tunneling current density resulting from the thick AlAs barriers.

To understand more fully the transport characteristics of this device, we measured the dependence of the base and collector currents on  $V_{be}$  with the collector-base junction shorted together; see Fig. 6. Note first that transistor gain is not obtained until the transistor  $V_{be}$  exceeds 2.4 V. Neglecting dynamic transport effects, this is sufficient voltage to allow transport across the device by thermionic emission over the AlAs tunnel barriers. The thick 5-nm AlAs barriers appear to inhibit current gain for lesser voltages.

The measured base current  $i_b$  is described by the ideal diode relation,  $i_b = i_o \exp(qV_{be}/\eta kT)$ , where  $i_o$  is the junction saturation current,  $\eta$  is the ideality factor, and  $V_{be}$  is the internal base-to-emitter voltage. The measured  $V_{be}$  is given by  $V_{be} = V_{bei} + i_b[R_b + (\beta + 1)R_e]$  where  $R_b$  is the base series resistance,  $R_e$  is the emitter resistance, and  $\beta$  is the transistor gain. Using these relations, the base current characteristics were fit to the equation

$$V_{be} = (\eta kT/q) \ln(i_b/i_o) + i_b(R_b + R_e)$$

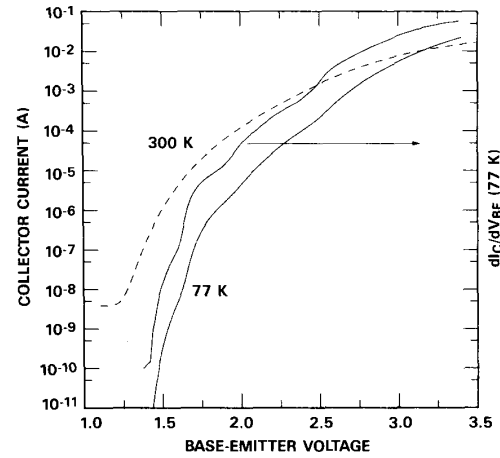


Fig. 5. Dependence of collector current on base-to-emitter voltage at  $V_{ce} = 2.5$  V. The dashed line shows the collector current dependence at room temperature, while the solid lines show the 77 K result. The derivative of the collector current with respect to the base-emitter voltage is shown to emphasize the collector current inflections.

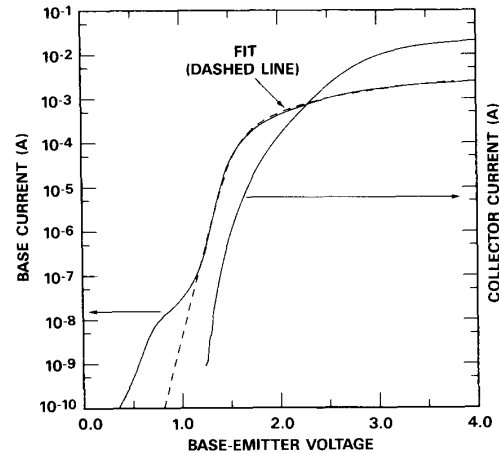


Fig. 6. Gummel plot for the BiQuaRTT at room temperature. Emitter area is  $9 \mu\text{m}^2$ ; base-to-emitter contact spacing is  $5 \mu\text{m}$ . (Same transistor as Fig. 5 measurement.)

where, in the region of the fit,  $\beta \ll 1$ . With an ideality factor of  $\eta = 2$ , the fitted data are shown by the dashed line in Fig. 6 where the free parameters become  $i_o = 1.55 \times 10^{-17}$  A and  $R_b = 830 \Omega$ . From an independent measurement [16] on this same device, the room-temperature emitter resistance is found to be  $440 \Omega$ . We therefore obtain a base resistance of  $390 \Omega$ . This measurement of the base resistance is consistent with the expected geometrical resistance of the quantum well between the emitter and base contacts. For this non-self-aligned process, the base-to-emitter spacing is  $5 \mu\text{m}$  and accounts for the high base resistance.

The fit in Fig. 6 is remarkably close for currents exceeding  $0.1 \mu\text{A}$ . The excess current, occurring below  $0.1 \mu\text{A}$ , is insensitive to surface treatment and shows a strong temperature dependence (see Fig. 7), characteristic of

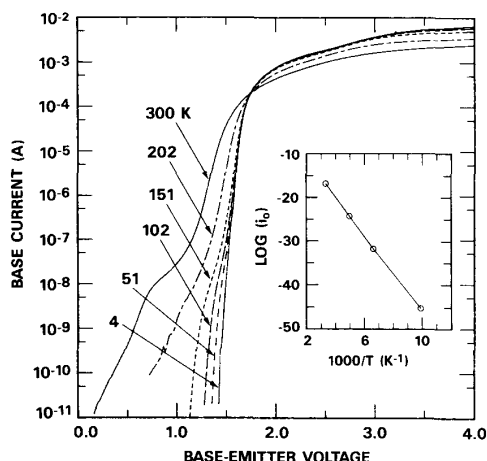


Fig. 7. Temperature dependence of the base current with  $V_{cb} = 0$  V. The inset shows the temperature dependence of the base-emitter junction saturation current with  $\eta = 2$ . (Same transistor as Fig. 5 measurement.)

generation through deep centers in the base-emitter transition region.

The temperature dependence of the base current is shown in Fig. 7 (after [17]). The base resistance of the device drops by several hundred ohms as the temperature is decreased, presumably due to increasing mobility. If each of the curves are fit as was done in Fig. 6, it is possible to obtain the base saturation current  $i_0$  as a function of temperature. A plot of the temperature dependence of  $i_0$  appears in the inset, from which an activation energy of 0.86 eV is obtained. This energy is below the 1.12-eV energy gap of bulk  $\text{In}_{0.23}\text{Ga}_{0.77}\text{As}$ . The InGaAs layer is under biaxial compression, which should increase the bandgap by 50 to 100 meV [18]. The measured activation energy of 0.86 eV then suggests that the saturation current is determined by generation through mid-gap deep levels. Twice 0.86 eV or 1.72 eV is equal to the total energy required to move an electron from the InGaAs valence band to the indirect X conduction band minimum of the AlAs barriers. By fitting the data in this way, we do not arrive at the energy for the tunneling transitions; however, these transitions are again apparent in the measured data as inflections in the current-voltage characteristics.

## V. DISCUSSION

One can compare the superlattice BiQuaRTT of [3] with the pseudomorphic BiQuaRTT described here, as both utilize a 15-nm quantum well, 5-nm tunnel barriers, and have identical geometrical device structures. The outstanding difference between these devices is that in the superlattice BiQuaRTT, room-temperature negative transconductance is observed, while in the pseudomorphic BiQuaRTT, the tunneling transport is considerably weaker. This can be understood in terms of the structural differences between the devices; however, a complete understanding of this class of quantum-well transistor will require further experimental and theoretical effort.

The superlattice BiQuaRTT utilized 5-nm  $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$  tunnel barriers compared with the 5-nm AlAs barriers described in the present device. The AlAs barriers result in a reduced resonant-tunneling current density since the larger AlAs barrier height reduces the transmission energy width of the RTD.

In the superlattice BiQuaRTT, the emitter and collector layers of the device are GaAs/ $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$  superlattices. These superlattices act to compress the energy distribution of electrons in the emitter and collector by the formation of minibands. The width of the first miniband is estimated to be approximately 9 meV. This can be expected to increase the peak-to-valley ratio of the RTD over that of bulk emitter and collector layer of the same average composition. It may be possible to obtain negative transconductance in this structure by tunneling the resonant tunneling between the two superlattices.

Considerable latitude for improvement of the pseudomorphic BiQuaRTT exists. The 5-nm AlAs tunnel barriers can be thinned to provide more ideal  $\Gamma$ -point tunnel barriers with larger resonant-tunneling current density. The 15-nm quantum-well thickness, which was intentionally made large to ease the contacting requirements, gives rise to many quantum-well energy levels. This is undesirable for a large negative transconductance device. The number of quantum-well states is readily reduced by thinning the quantum well. The thinner base will require higher quantum-well doping and a self-aligned transistor geometry to minimize the base resistance.

## VI. CONCLUSIONS

We have demonstrated a pseudomorphic BiQuaRTT in which contact is made to a Be-doped quantum well. The transport characteristics show evidence of tunneling-current control by modification of the quantum-well potential. The voltages at which the transistor is biased into resonance are well predicted by a self-consistent numerical simulation of the electrostatic potential. Measurements of the temperature dependence of the device transport characteristics indicate that improved device performance can be expected with reduced base resistance and thinner AlAs tunnel barriers.

*Note added:* The idea of contacting the p-doped quantum well of an RTD to control the tunneling current has been previously and independently conceived [19].

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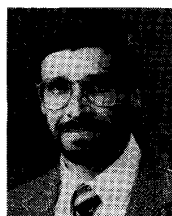
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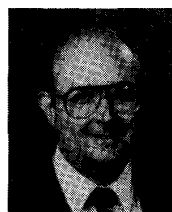
**Alan C. Seabaugh** (S'78–M'85) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Virginia. His doctoral dissertation concerned the measurement and interpretation of photocurrent transients in semi-insulating GaAs using a novel ac impedance bridge technique.

From 1979 to 1986, he was employed by the National Bureau of Standards where he developed a variety of electronic and photoelectronic measurement techniques for characterizing compound

semiconductors. He joined the Central Research Laboratories of Texas Instruments Incorporated in 1986, where he worked on microwave MOD-FET's, selective reactive-ion etching, and heterojunction C-V profiling. In early 1988, he changed tasks to develop resonant tunneling transistors. His current interests are in the transport properties of hot-electron and resonant-tunneling devices. On a part time basis, he lectures at the University of Texas at Dallas.

Dr. Seabaugh is a member of the APS.

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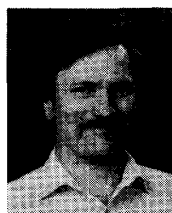


**William R. Frensley** (M'78–SM'84) received the B.S. degree in physics from the California Institute of Technology, Pasadena, in 1973 and the Ph.D. degree in physics from the University of Colorado, Boulder, in 1976. His dissertation research concerned the theory of the electronic structure of semiconductor heterojunctions. He continued this work in a post-doctoral position at the University of California at Santa Barbara.

In 1977, he joined the Central Research Laboratories of Texas Instruments Incorporated, where at first he did experimental and theoretical work on GaAs MES-FET's. He has also been involved in the development of GaAs bipolar transistor IC's and more novel, vertically structured GaAs FET's. His research interests are presently directed toward the theory of electron transport in quantum-scale semiconductor devices.

Dr. Frensley is a member of the American Physical Society. He was an Associate Editor of IEEE TRANSACTIONS ON ELECTRON DEVICES from 1983 to 1986.

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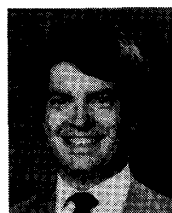


**John N. Randall** (S'80–M'81) received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of Houston in 1975, 1977, and 1981, respectively. His work at the University of Houston involved the microfabrication of sub-tenth-micrometer structures with e-beam and X-ray lithography to be used in an e-beam memory system.

After receiving the Ph.D., he joined M.I.T.'s Lincoln Laboratory where he worked for three and a half years. At the Lincoln Laboratory, he was also involved with masked ion-beam lithography, but was also involved with reactive-ion etching, X-ray lithography, low-pressure chemical vapor deposition, and other microfabrication techniques. He joined Texas Instruments Incorporated in 1985 and is a member of the technical staff in the Central Research Laboratories. He is presently responsible for microfabrication of quantum effect devices. Other work at Texas Instruments has concerned the investigation of masked ion-beam lithography, which included development and modeling of ion beam masks. He has published in numerous technical journals.

Dr. Randall is a member of the AVS and SPIE.

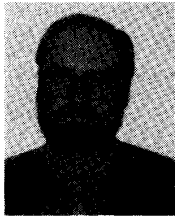
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**Mark A. Reed** (M'84–SM'87) received the B.S. degree (Honors) in physics in 1977, the M.S. degree in physics in 1979, and the Ph.D. degree in solid-state physics in 1983 from Syracuse University.

He then joined Texas Instruments Incorporated as a Member of the Technical Staff in the Central Research Laboratories. His research activities at TI have included the investigation of mesoscopic systems, tunneling phenomena in heterojunction systems, artificially structured materials and devices, localization phenomena, and high magnetic field effects in semiconductors. In 1986 he became an Adjunct Professor of Physics at Texas A&M University. In 1988 he was elected to Senior Member of the Technical Staff at TI. He is the author of more than 40 professional publications in numerous journals. He is co-editor of the book *Nanostructure Physics and Fabrication* and is the author of several book chapters. He holds six U.S. patents.

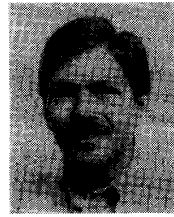
Dr. Reed is a member of the APS, Sigma Xi, and the OSA.



**Dewey L. Farrington** received the A.S. degree in electronic technology from Oklahoma State University in 1978 and the B.S. degree in physics from the University of Texas, Dallas, in 1987.

He joined Texas Instruments in 1978. He spent two years in the Missile Division before joining the Radar Division as a Field Representative in Europe for the Tornado (MRCA) project at customer locations (one year in England and two years in Italy). Upon returning to Dallas, he moved to the Central Research Laboratories as a Research

Assistant in the SIMS Laboratory. He is presently a Member of the Technical Staff at TI and is primarily responsible for the SIMS Laboratory.



**Richard J. Matyi** received the Ph.D. degree in materials science from Northwestern University in 1982.

He joined Texas Instruments Incorporated in 1982. His work included X-ray diffraction analysis of semiconductor materials, the growth of compound semiconductor structures for microwave and ultrasmall electronics applications using molecular-beam epitaxy, and the cointegration of GaAs and silicon device structures. He is now an Assistant Professor in the Department of Materials Science and Engineering at the University of Wisconsin, Madison.